Recent trends in global ocean chlorophyll

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Received 21 October 2004; revised 1 December 2004; accepted 12 January 2005; published 8 February 2005.

[1] A 6-year time series of remotely-sensed global ocean chlorophyll was evaluated using linear regression analysis to assess recent trends. Global ocean chlorophyll has increased 4.1% ($P < 0.05$). Most of the increase has occurred in coastal regions, defined as bottom depth < 200 m, where an increase of 10.4% was observed. The main contributors to the increase were the Patagonian Shelf, Bering Sea, and the eastern Pacific, southwest African, and Somalian coasts. Although the global open ocean exhibited no significant change, 4 of the 5 mid-ocean gyres (Atlantic and Pacific) showed declines in chlorophyll over the 6 years. In all but the North Atlantic gyre, these were associated with significant increases in sea surface temperature in at least one season. These results suggest that changes are occurring in the biology of the global oceans. **Citation:** Gregg, W. W., N. W. Casey, and C. R. McClain (2005), Recent trends in global ocean chlorophyll, *Geophys. Res. Lett.*, *32*, L03606, doi:10.1029/2004GL021808.

1. Introduction

[2] The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission has provided the first continuous, long-term observations of global ocean chlorophyll from space. This rigorously calibrated and validated data set spans >6 years beginning in 1997. Using SeaWiFS chlorophyll observations, the responses of ocean biology to seasonal, regional, and interannual events have been observed comprehensively for the first time. In this paper we use the SeaWiFS record to evaluate the question: Are there current trends in global ocean chlorophyll?

2. Methods

[3] SeaWiFS Level-3 Version 4 monthly 9-km data were obtained from the NASA Goddard Earth Sciences Distributed Active Archive Center and interpolated to 25-km resolution. Inland seas and isolated bays and inlets were masked out. Although SeaWiFS began taking data in Sep 1997, we only used data from the period 1998–2003 because these represented complete annual records from the SeaWiFS lifetime. Trends were assessed by 1) subtracting monthly climatological mean values from each month to remove the background (producing monthly anomalies), 2) averaging the 12 monthly anomalies of each year to remove the seasonal signal (producing annual mean anomalies), 3) computing best-fit linear trends using regression analysis, and 4) assessing statistical significance of the trends [*Zar*, 1976]. A statistically significant trend was one that exceeded the 95% confidence level. Trends in chlorophyll are reported as percent, computed from the linear trend, with the chlorophyll value at the y-intercept representing the starting point. We recognize that this methodology increases our chances of Type-II errors (not detecting a trend when one exists), but it is our preference to err in this direction rather than in the direction of a Type-I error (falsely detecting a trend when one does not exist).

[4] Monthly climate data fields were obtained for the 1998–2003 period. Sea surface temperature (SST; NOAA/NASA Advanced Very High Resolution Radiometer [AVHRR] Oceans Pathfinder Project) was obtained at 4-km spatial resolution and interpolated to 25-km to match the SeaWiFS resolution used in the analysis. Daytime and nighttime data were equally weighted. Other climate data fields were only available at lower spatial resolution, and were interpolated to 1-degree, monthly resolution. These included scalar wind stress and net short-wave radiation (NOAA National Center for Environmental Prediction).

[5] Trends in ocean chlorophyll were evaluated globally, and were subdivided into coastal regions (bottom depth < 200 m) and open ocean. We also computed trends on a point-by-point basis to try to understand where changes were occurring. Based on a significance value of 95% ($P < 0.05$) we derived a global map of trends (Figure 1). All clusters of pixels with significant trends were isolated as regions of interest, and the data were then averaged within the region. For oceanic gyre regions, we chose areas where the climatological chlorophyll over the six years was ≤ 0.1 mg m^{-3}. A minor exception was the South Atlantic gyre region, where southerly pixels outside the 0.1 mg m^{-3} limit were included. The maximum value was 0.29 mg m^{-3}. Only regions for which significant trends were observed are identified in Figure 1. These regions are intended to be biogeographically coherent at the same time grouping similarly trended points. Seasonal analyses were performed in a similar manner as the annual analyses described above, with seasons corresponding with the Northern Hemisphere convention:

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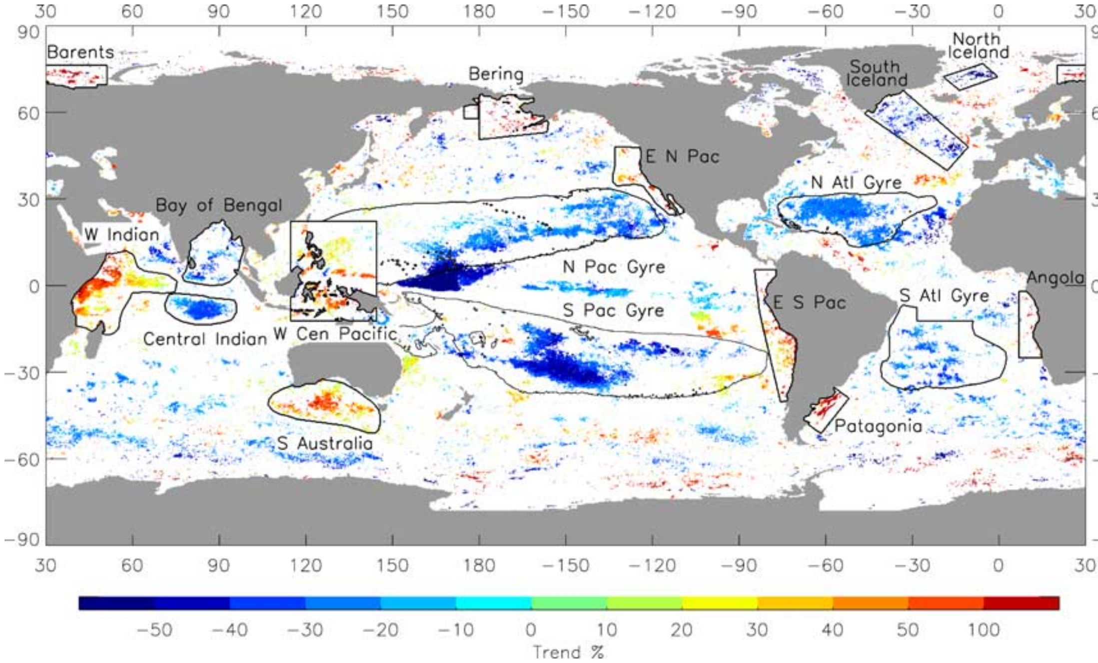

Figure 1. Regions defined by coherent distribution of 25-km grid points where chlorophyll concentrations indicated a significant trend (P < 0.05) over the 6-year data record of SeaWiFS. Only regions where significance was found within the region as a whole are shown here.

winter (Jan–Mar), spring (Apr–Jun), summer (Jul–Sep), and autumn (Oct–Dec).

3. Results and Discussion

3.1. Global Trends

[6] Global ocean chlorophyll increased 4.13% from 1998 to 2003 ($P < 0.05$; Table 1). When subdivided into coastal and open oceans, only the coastal regions indicated a significant trend (Table 1). The coastal trend was large and positive (10.4%).

[7] To estimate the effects of El Niño-Southern Oscillation (ENSO) events on the longer-term detection of trends, we eliminated all chlorophyll data in the Pacific equatorial upwelling region (10°N and S) plus moderately high chlorophyll (>0.45 mg m^{-3}, determined using the SeaWiFS 6-year climatology) along the eastern coasts of the Pacific, extending to 40°N and S. The global trends showed negligible change (global trend = 4.11%), as did the open ocean and coastal trends (open ocean = 0.6%, coastal = 10.6%). Therefore, we believe that the global trends observed here were not influenced by the timing and magnitude of ENSO events.

[8] The distribution of the 6-year trends (Figure 2) illustrates where the major changes have occurred. This map does not indicate significant trends, as in Figure 1, but

Table 1. Global Trends in Ocean Chlorophyll 1998–2003[a]

Region	N	Slope	Intercept	Error	Trend	Significance
Global	560247	0.00261	−0.007	±0.002	+4.13%	P < 0.05
Coastal	51979	0.03687	−0.092	±0.033	+10.35%	P < 0.05
Open Ocean	530579	0.00040	−0.001	±0.003	+0.90%	NS

[a]NS indicates not statistically significant at the 95% confidence level. N is the maximum number of values in a given year, error represents the standard error of the estimate, and trend is reported as percent change over 6 years.

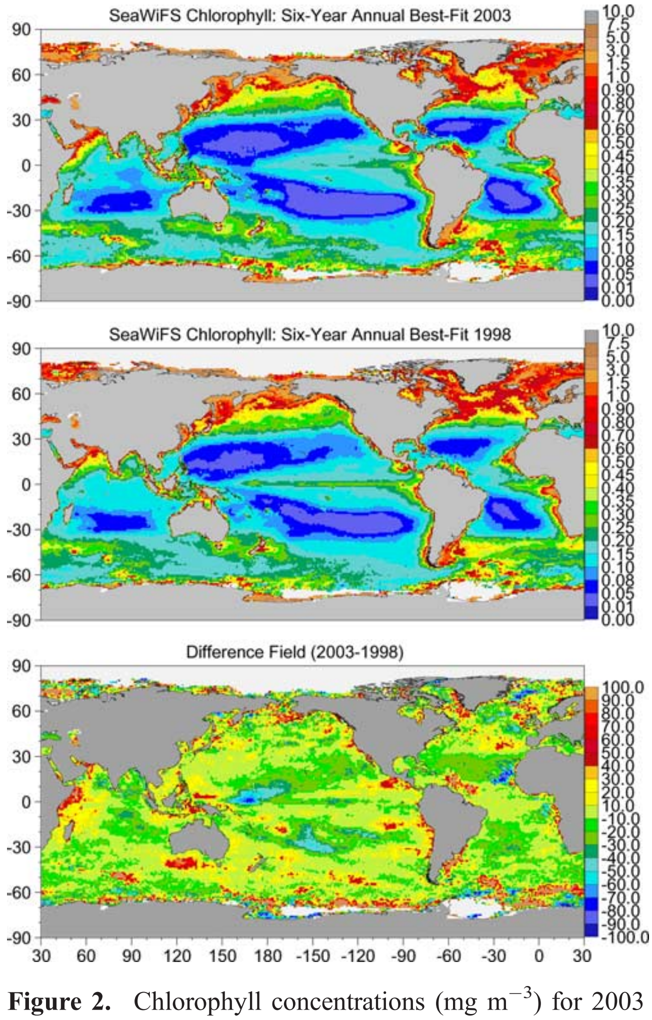

Figure 2. Chlorophyll concentrations (mg m^{-3}) for 2003 and 1998 lying on a best-fit linear trend, and the difference (2003–1998) in percent.

Table 2. Significant Trends Over 6 Years in Coastal Ocean Regions[a]

Region	N	Slope	Intercept	Error	Trend
Patagonian Shelf	1177	0.193	−0.481	±0.246	+67.8%
Bering Sea	2713	0.125	−0.338	±0.118	+36.4%
Namibian/Angolan Coast	171	0.325	−0.809	±0.385	+34.2%
Somalian Coast	297	0.076	−0.189	±0.083	+44.9%
California/Mexican Shelf	242	0.287	−0.717	±0.360	+60.3%
Peru/Chile Shelf	182	0.160	−0.404	±0.157	+23.4%

[a]N indicates maximum number of values observed by SeaWiFS within the region in a given year.

provides an overview of the changes as represented by a difference field. The chlorophyll images represent best-fit values for 1998 and 2003, rather than the actual data. Specifically, 1998 data are the y-intercept of the linear equation for each grid point, and 2003 are the values at the end point of the equation. This methodology enables us to minimize the effects of interannual variability in the images and the difference field.

3.2. Coastal Trends

[9] On the coasts, noteworthy positive trends were apparent in the Bering Sea, Patagonian Shelf, the Somalian shelf in the western Indian Ocean, and Namibian/Angolan coast in the eastern South Atlantic (Table 2). There were also significant positive trends along the shelf regions of the eastern Pacific; however, these may be a residual influence from the low chlorophyll resulting from the 1997–1998 El Niño at the beginning of the time series.

[10] There are indications that some of the increases in chlorophyll may be due to climate change. The Patagonian Shelf region has undergone a significant decrease of 0.78°C since 1998, which is consistent with increased upwelling and higher chlorophyll (67.8%).

[11] However, the increased chlorophyll in the Bering Sea was accompanied by a 1.53°C increase in SST since 1998. Increased SST in spring can cause a larger bloom, but nutrient exhaustion appeared to cause a net decrease in annual mean chlorophyll [*Gregg and Conkright*, 2002]. The statistically significant increased SST occurred in the spring and summer. This partially coincided with the statistically significant increases in chlorophyll, which occurred in winter and spring, i.e., the pre-bloom and bloom maximum periods. Additionally, a significant increase in shortwave radiation (+6.7%) was observed. The increased light at the surface, along with increased SST, may have been sufficient to produce higher blooms in winter and spring. Alternatively, abundant populations of coccolithophores have been observed in the Bering Sea recently in summer [*Napp and Hunt*, 2001], and recent high reflectances in winter have been attributed to suspended sediments [*Broerse et al.*, 2003]. It is not clear if these constituents affected the retrieval of ocean chlorophyll and the long term trends.

3.3. Open Ocean Trends

[12] Although there was no statistically significant trend in the global open oceans over the 6-year SeaWiFS record, some regions experienced significant changes. Four of the 5 ocean gyres (North and South Pacific, North and South Atlantic) showed major declines (Table 3 and Figure 3). For all but one of these gyres (North Atlantic), SST also increased significantly in at least one season (Figure 3). This strongly suggests warming is occurring in the ocean central gyres, resulting in declining chlorophyll concentrations. In a different approach using nearly the same time period, *McClain et al.* [2004] found expanding gyres in the Atlantic and Pacific by tracking the change in number of SeaWiFS grid points <0.07 mg m^{-3}. This generally supports the findings here.

[13] Although it is not typically classified as a gyre region, a similar large decline occurred in low chlorophyll waters just north of the Central Indian gyre (Table 3), in effect creating a new or extended gyre region (Figure 2).

Table 3. Significant Trends in Chlorophyll From SeaWiFS Over 6 Years in Open Ocean Regions (Bottom Depth ≥ 200 m)[a]

Region	N	Trend	SST	Wind Stress	Shortwave Radiation
Gyres					
North Pacific	33529	−16.3%	+0.31°C (an)		−2% (at)
North Atlantic	10716	−21.0%			
South Pacific	40994	−10.6%	+0.60°C, 0.42°C (sp, sm)		
South Atlantic	13875	−15.9%	+0.51°C (sm)	−26% (sm)	
Central Indian (north of gyre)	3346	−20.1%	+0.84°C (sm)		−3% (an)
Decreasing Regions					
Atlantic N Iceland	1399	−59.2%			+9% (an)
Atlantic S Iceland	6506	−20.1%		−37%, −47% (sm, at)	+3% (sm)
Bay of Bengal	4612	−16.7%			
Increasing Regions					
Barents Sea	2115	72.4%			
Western Indian	7947	37.2%			
Eastern North Pacific	2689	31.6%			
Eastern South Pacific	4183	30.4%			
Southern Australia	7107	28.9%	+0.56°C (sp)		
Offshore Angola	2042	25.3%		−24% (at)	
West Central Pacific	12279	17.3%	−0.39°C (an)	+26% (an)	

[a]N indicates maximum number of values observed by SeaWiFS within the region. Significant trends for associated climate variables are shown. The time domain for which the significance was obtained is shown: an = annual, wn = winter, sp = spring, sm = summer, and at = autumn.

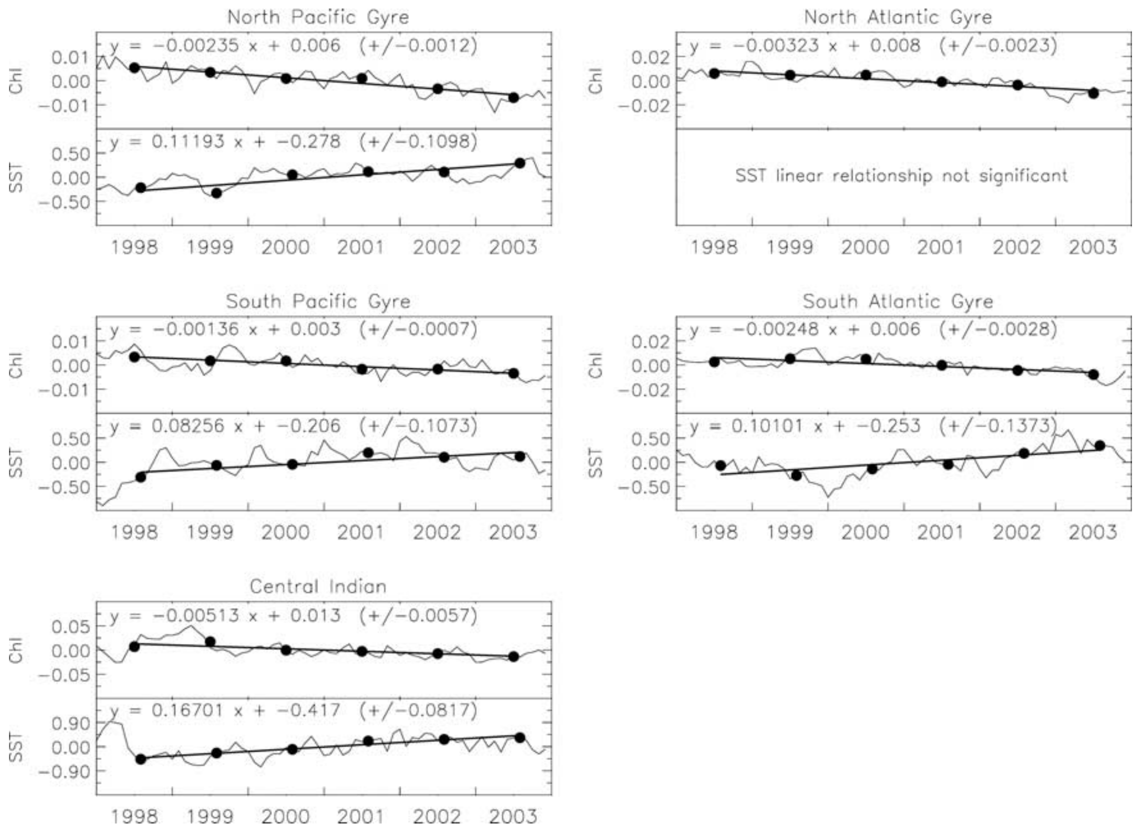

Figure 3. Linear trends of chlorophyll concentration anomalies from SeaWiFS (mg m^{-3}) and SST anomalies from AVHRR (°C) for each of the Atlantic and Pacific gyres. Only statistically significant trends ($P < 0.05$) are shown. The line equation for the trend is shown on each plot, with the standard error of the estimate in parentheses. The South Pacific, South Atlantic, and Central Indian represent the summer season SST trend, and the North Pacific represents the annual SST trend. All of the chlorophyll trends represent the annual trend.

Here, a decrease of >20% occurred in chlorophyll concentration, accompanied by a 0.8°C increase in SST in summer. Additionally, a 3% decrease in surface shortwave radiation may have contributed to the decline in chlorophyll, by reducing light available for photosynthesis.

[14] Other open ocean regions where significant decreases were observed included two locations in the North Atlantic, north and south of Iceland (Table 3). Both regions experienced increases in shortwave radiation in summer, which may have contributed to surface heating and stratification. The southern portion also experienced major declines in scalar wind stress in summer and autumn, which also acts to increase stratification and reduce nutrient exchange with deeper layers. Additionally, the Bay of Bengal experienced a 17% decline in chlorophyll over the 6-year time period (Table 3).

[15] Seven open ocean regions increased in chlorophyll over the time series, counterbalancing the declines observed in the gyres and three other regions (Table 3). The largest increase was observed in the Barents Sea (72%). The smallest occurred in the western central Pacific near Indonesia and the Philippines, where a 17% change was observed. The latter change appeared to be related to a 0.39°C decrease in SST along with a 26% increase in scalar wind stress. Together these climate variables suggest increased mixing and/or upwelling that is consistent with increased primary production.

[16] The western Indian Ocean off the coast of Somalia showed the second largest increase in chlorophyll concentrations among the open ocean regions (37%; Table 3). The increases were similar to those observed in the coastal area off Somalia.

[17] Finally, the area just south of Australia was the only coherent portion of the Southern Ocean to experience significant trends over the SeaWiFS record (Table 3). Here a 29% increase in chlorophyll was accompanied by a 0.56°C increase in SST in spring. Although these trends are contrary to what is expected, in the Southern Ocean deep mixed layers are present even in the local summer, which tend to limit light availability. Warmer ocean temperatures can produce a shallower mixed layer, allowing more light availability in the mixed layer and stimulating phytoplankton growth. Additionally, this portion of the Southern Ocean has been identified as an iron-limited region [*Boyd et al.*, 2001]. We do not have a continuous data record for iron deposition.

4. Concluding Remarks

[18] The 6-year time series of global ocean chlorophyll from SeaWiFS is insufficient to unambiguously characterize long-term trends. It is also difficult to relate the trends to climate decadal oscillatory behavior, such as the North Atlantic Oscillation and Pacific Decadal Oscillation,

among others. However, it is sufficiently long to minimize the influence of ENSO events. This analysis is intended to serve as a benchmark for current trends in chlorophyll data.

[19] *Gregg and Conkright* [2002] recorded a decline in global open ocean chlorophyll from the historical record (1979–1986) to the present (1997–2000 in their analysis). The present analysis suggests that further declines in open ocean chlorophyll are not occurring. However, the observed increase in chlorophyll in coastal regions is a very important result from the present study. *Bakun and Weeks* [2004] have suggested a warming Earth can enhance coastal upwelling. Conflicting relationships between the increases and SST in the Bering Sea and Patagonian shelf, two of the largest changes, are difficult to reconcile, but the possibility of anthropogenic influences on these and other coastal areas cannot be ignored. This study is not intended to explain all of the open ocean and coastal trends, but rather, to document the current trends and suggest climatic relationships when possible. More concrete evidence of the trends and their causes will require a longer term time series and more focused analyses in specific regions.

[20] **Acknowledgments.** We thank the NASA SeaWiFS Project, Orbimage Corp., and GES-DAAC for chlorophyll data. This work was supported by NASA grant 428-88-12-20.

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